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# PROGRESS IN SPACE CHARGE LENS DEVELOPMENT*

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## Summary

A number of space charge lens electrode geometries have been studied for use at very high beam currents at low energy, and for precision optics at MeV energies. One such lens mounted very near a Duo-plasmatron extractor delivered a 30-keV beam of $H^+$ ions through an analyzing magnet at a current of 175 mA for a period of six hours. Another produced a focal spot of diameter 0.2 mm when a 1-cm diameter beam of 1.2-MeV protons was focussed 90 cm from the lens. This paper also describes observations on self-sustaining discharge in the lenses. A very interesting rotation of the lens optic axis about the geometric axis at a frequency near the drift frequency occurs when the vacuum is spoiled by electrode outgassing.

## Introduction

A space charge lens consists of a cylindrical electron trap produced with ring electrodes in an axial magnetic field. The electric field strength within the trapped electron cloud increases with radius and is responsible for the focusing of a positive ion beam. Reference 1 outlines the history and principles of such lenses. That paper and the references contained therein will serve as an introduction to this paper.

## The Permanent Magnet Lens

Figure 1 is a diagram of a two-electrode lens at Livermore in which the magnetic field is produced with permanent magnets† that deliver flux radially midway between the two electrodes. Flux is returned to the center through iron. The electron traps are kept filled by a self-sustaining discharge. Enough photoelectrons and ion-produced electrons are released from grounded surfaces to replace those that are captured at the electrodes.

When the discharge is present, blue lines appear on the axis of each electrode, and these are used to align the lens. The blue lines have appeared in all the electrode geometries we have studied and are probably caused by recombination of positive ions which collect near the lens axis.

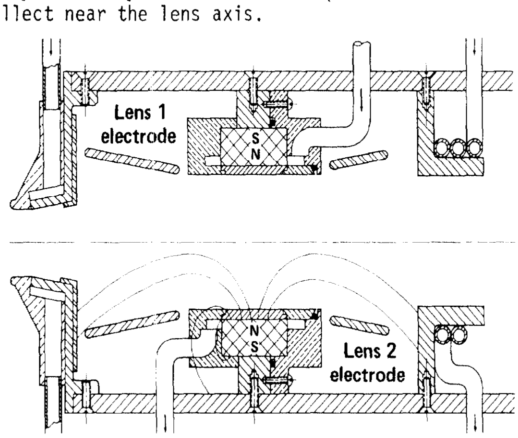


*Fig. 1. The LLL permanent magnet lens. Overall length is approximately 18 cm.*

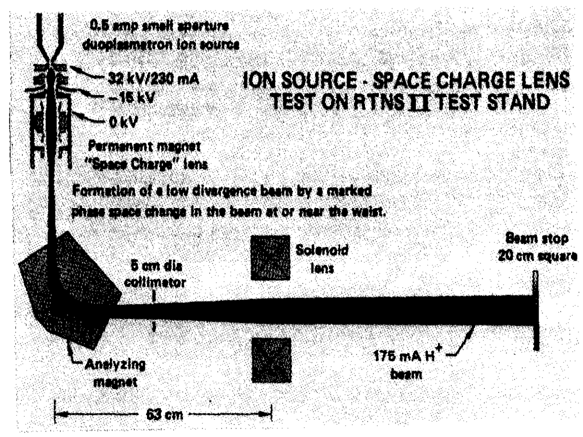


*Fig. 2. The permanent magnet lens on the RTNS-II test stand.*

Figure 2 schematically shows the lens placed very near the extractor of a duoplasmatron ion source mounted on the RTNS-II ion source test stand.[2] In one test, 175 mA of analyzed protons were delivered for a period of six hours. Lens voltage was 4.2 keV and electrode current was 5 mA.

A marked phase space change occurs near the beam waist just beyond the lens. The change is believed due to the effect first reported by Kelley.[3] A large fraction of the beam beyond crossover appears to propagate in a rod or core, with anomalously small divergence.

## The Nine Ring Lens

Figure 3 is a photograph of a lens we are studying at the University of Oregon for use with MeV protons. The question of most interest with this lens is: Can one use a space charge lens as a precision demagnifier for a proton microprobe?

Nine rings of ID 3.5 cm are closely fitted inside a 4 cm ID glass tube. They are spaced 2.25 cm apart

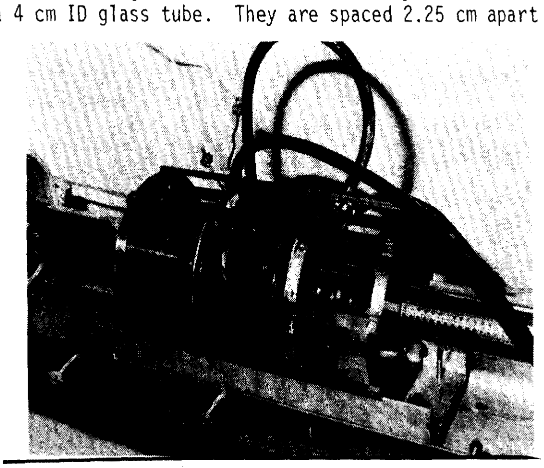

*Fig. 3. The University of Oregon nine ring lens. Two of the nine rings can be seen in the Pyrex beam tube just to the right of the solenoid.*

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†Thirteen rare earth cobalt magnets, 1.25 cm square by 2.5 cm long.

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for a length of 18 cm. The solenoid is 12 cm long and is symmetrically placed relative to the central ring. Magnetic field strength is 925 gauss at 12 amperes coil current. It is not yet clear whether the iron return path seen in Fig. 3 is helpful. High voltage is brought to the electrodes between the inner glass tube which supports the rings, and the outer 2.5 cm ID pyrex beam tube. The system is pumped to a base pressure of $2 \times 10^{-7}$ Torr by a four inch oil diffusion pump with a water cooled baffle.

After pumpdown, several hours are required to outgas the lens electrodes. After a day without voltage the electrodes again outgas for about an hour. After outgassing, the current-voltage characteristic assumes the character shown in Fig. 4. The reason for the exponential increase of current with voltage is not known.

Measured and Deduced Parameters of the Nine Ring Lens

So far we have achieved a focussed beam spot size of 0.2 mm for 1.2 MeV protons at a focal length of 90 cm with a one cm square lens aperture. A lens voltage of 6 kV is required. From the small aberrations one concludes that the radial impulse delivered by the lens field varies quite linearly with radius.

One deduces the effective length of the trap, $\langle \ell \rangle$, from focal length, f, lens voltage, V, and electrode radius, R, and proton accelerating voltage, $\phi$, as

$$\langle \ell \rangle = \frac{\phi}{V}\frac{R^2}{f} = 6.8 \text{ cm.} \quad \text{(see Ref. 1)}$$

From Gauss' law and the fact that the radial electric field varies as $2Vr/R^2$, where R is ring radius, one deduces a trapped electron number density of $4 \times 10^9$ el/cm$^3$. Total trapped charge, $\pi R^2 \langle \ell \rangle \rho$, is $4.5 \times 10^{-8}$ Coul.

The mean electron storage time in the trap is equal to the stored charge divided by the lens current (from Fig. 3) and is given in MKS units by

$$\tau = 4\pi\varepsilon_0 \langle \ell \rangle \cdot 10^6 V \exp(-V/1320)$$
$$= 4.25 \times 10^{-4} \text{ sec at } V = 6 \text{ kV} \quad .$$

Note that the mean storage time is decreasing sharply with voltage at 6 kV.

The electron drift frequency ($f = V(r)/\pi r^2 B$) is observable with a loop antenna at the end of the lens, and it monitors the internal fields. We find that as lens voltage is raised, the drift frequency increases until the lens can no longer keep itself supplied by self-excitation because of the decreasing storage time. The frequency then decreases, the lens becomes weaker, and the trap may suddenly empty itself as lens voltage is raised. When restriking the discharge with electrons from a hot filament, lens voltage must be greatly reduced and then brought back up after restriking.

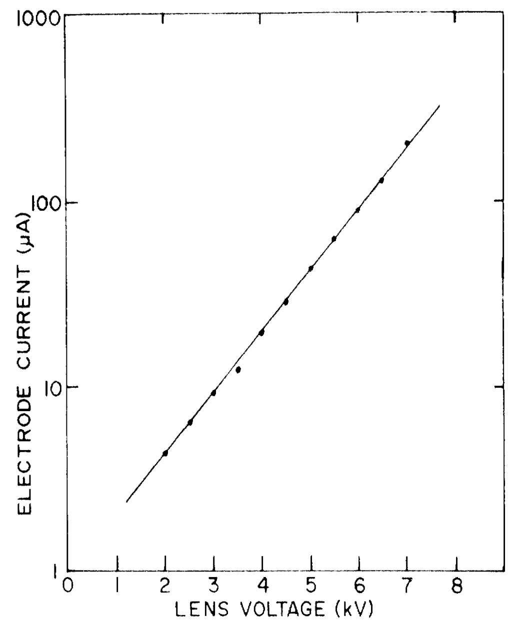


*Fig. 4. Current vs voltage characteristic of the nine ring lens after outgassing. The solid line is given by $i = 10^{-6} \exp(V/1320)$.*

Table 1 collects several observations on lens strength, aberrations, and self-excitation for several biasing conditions of the lens electrodes. For each case, alternate electrodes were electrically floating and bias was applied to outer, intermediate, and center rings. Bias was derived from taps on a resistor string of ten two-megohm resistors.

Questions

The following questions appear to be important in achieving the level of understanding of space charge lenses that will be necessary to use them for precision optical applications.

1. Why does lens current increase exponentially with voltage?
2. How should one dispose the grounded surfaces for best self excitation? Is it reasonable to expect self excitation at ultra-high vacuum?
3. How good must the vacuum be? The blue line on axis casts a "shadow" in an almost focussed beam in the sub-millimeter region. The shadow becomes smaller at better vacuum.
4. How accurately can one control the fields? In particular, why does the electric field vary like r for a variety of electrode structures with self excitation at good vacuum?

Table 1. Observations on lens strength, abberations, and self excitation for several electrode biases.

| Electrode Bias (Volts) | | | Observations (after outgassing) |
|---|---|---|---|
| Center | Intermediate | Outer | |
| V | 0.9 V | 0 | Strongest lens. Small aberrations. Not self starting. (A hot filament is used.) |
| V | 0.9 V | 0.3 V | Weaker lens. Larger aberrations. |
| V | 0.5 V | 0 | Weak lens. Self starting. |
| V | V | 0 | Not self excited. |

## Magnetron Rotation of the Lens Optic Axis

When the lens vacuum is spoiled ($P > 10^{-6}$ Torr) by electrode outgassing, the lens can suddenly go into a mode which causes the focussed beam to draw a circle at the focal plane. The sense of rotation of the beam spot on the focal plane as deduced with current probes is the same as that of the electron drift in the lens. The rotation frequency is the same as (or very near) the electron drift frequency. The radius of the focal circle increases with gas pressure. Evidently, the optic axis of the lens rotates around the geometric axis at the drift frequency.

That the effect of this magnetron rotation on a charged particle beam is substantial can be seen by the fact that we have seen focal circles 1 cm in diameter when 1.2-MeV protons were focussed at 90 cm. Also in an experiment with 30-keV protons, a six milliampere beam was chopped at 9.8 MHz by using a small aperture at the focal circle and 5 ns current pulses were observed on a downstream probe. The effect might be controlled with a split anode lens and it might be useful for chopping high current beams.

## Acknowledgments

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## References

(1) R. Booth and H. W. Lefevre, Nucl. Instr. Meth. 151, 143 (1978).

(2) J. E. Osher, Inst. Phys. Conf. Ser. No. 38 Ch. 5 (1978).

(3) G. C. Kelley, IEEE Trans. on Nucl. Sci. NS14(3), 29 (1967).

(4) H. W. Lefevre and R. Booth, Bull. Am. Phys. Soc. 24, 196 (1979).